Journal of Coastal Research	29	1	18–30	Coconut Creek, Florida	January 2013

Modeling of Coastal Inundation, Storm Surge, and Relative Sea-Level Rise at Naval Station Norfolk, Norfolk, Virginia, U.S.A.

Honghai Li[†], Lihwa Lin[†], and Kelly A. Burks-Copes[‡]

[†]U.S. Army Engineer Research & Development Center
Coastal and Hydraulics Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199, U.S.A.
Honghai.Li@usace.army.mil

[‡]U.S. Army Engineer Research & Development Center
Environmental Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199, U.S.A.

ABSTRACT

Li, H.; Lin, L., and Burks-Copes, K.A., 2013. Modeling of coastal inundation, storm surge, and relative sea-level rise at Naval Station Norfolk, Norfolk, Virginia, U.S.A. *Journal of Coastal Research,* 29(1), 18–30. Coconut Creek (Florida), ISSN 0749-0208.

The potential risk and effects of storm-surge damage caused by the combination of hurricane-force waves, tides, and relative sea-level-rise (RSLR) scenarios were examined at the U.S. Naval Station, Norfolk, Virginia. A hydrodynamic and sediment transport modeling system validated with measured water levels from Hurricane Isabel was used to simulate two synthesized storms representing 50-year and 100-year return-period hurricanes, a northeaster, and five future RSLR scenarios to evaluate the combined impacts of inundation on this military installation in the lower Chesapeake Bay. The naval base topography and nearshore water body of Hampton Roads were included in the coastal modeling system (CMS), a suite of surge, circulation, wave, sediment transport, and morphology evolution models. The modeling domain was a rectangular area covering the entire Naval Station Norfolk in the Hampton Roads and the mouths of the James and Elizabeth rivers. A variable-resolution grid system was created with a finer resolution of 10 m in the naval base and a coarser resolution of 300 m in the regions away from the base. The boundary-forcing conditions to the CMS were regional storm surge produced by the ADvanced CIRCulation (ADCIRC),and wave conditions by the Simulating WAve Nearshore (SWAN) model. The CMS calculated the local water-surface elevation and storm-surge inundation for combined RSLR, surge, waves, and wind. Results indicate that synthetic storms would cause extensive inundation of coastal land around the naval base. Approximately 60% of the land would be under water with the 100-year storm for the present sea level, and 80% for estimated RSLR of 2 m.

ADDITIONAL INDEX WORDS: *Nearshore hydrodynamic modeling, waves, synthetic tropical storms, extratropical storms, Hurricane Isabel, land flooding*.

INTRODUCTION

Global sea-level rise (SLR) ranging from 0.5 to 2 m has been predicted over the next century, from 2000 to 2100 (IPCC, 2007; Pfeffer, Harper, and O'Neel, 2008). Relative SLR (RSLR) can be greater than the global trend because of local effects such as subsidence. The combination of an increase in SLR and coastal storms, including hurricanes (tropical storms) and winter storms (extratropical storms), will increase the risk of storm-surge inundation in exposed coastal regions. On average, 1.6 hurricanes per year in the last century have made landfall on the U.S. coastline (Smith, 1999). For the East Coast of the United States, Hirsch, DeGaetano, and Colucci (2001) developed a climatology of winter storms based on historical data and estimated an average of 12 storms for each winter season. Sea-level rise combined with strong storms will worsen beach erosion, increase damage to coastal infrastructure, and cause major shoreline change (McLean *et al.*, 2001). It is essential to quantify the risk associated with SLR and storm damage to provide decision makers with relevant guidance regarding existing and future coastal infrastructure development.

Military coastal installations and facilities support a range of activities vital to national security and provide significant benefits to the local economy. These facilities carry out diverse tasks from outdoor training activities (ground, ports, harbors, and navigation) to air combat. The Naval Station Norfolk, in Norfolk, Virginia, was selected as a demonstration site for a risk-assessment study to understand the effects of RSLR and coastal storms on the physical installation as well as nearshore physical processes. The coastal modeling system (CMS) was applied to calculate the inundation and navigation channel shoaling for various future RSLR scenarios. Herein, we describe the implications of potential RSLR estimates and storm surges on total inundation; a subsequent paper will discuss results relating to sediment transport and navigation channel shoaling.

METHODOLOGY

The CMS is an integrated suite of numerical models for simulating water-surface elevation, current, waves, sediment

DOI: 10.2112/JCOASTRES-D-12-00056.1 received 17 March 2012; accepted in revision 17 June 2012.
Published Pre-print online 17 September 2012.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JAN 2013	**N/A**	**-**

4. TITLE AND SUBTITLE
Modeling of Coastal Inundation, Storm Surge, and Relative Sea-Level Rise at Naval Station Norfolk, Norfolk, Virginia, USA

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Li, Honghai; Lin, Lihwa; Burks-Copes, Kelly A.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS; US Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT
The potential risk and effects of storm-surge damage caused by the combination of hurricane-force waves, tides, and relative sea-level-rise (RSLR) scenarios were examined at the U.S. Naval Station, Norfolk, Virginia. A hydrodynamic and sediment transport modeling system validated with measured water levels from Hurricane Isabel was used to simulate two synthesized storms representing 50-year and 100-year return-period hurricanes, a northeaster, and five future RSLR scenarios to evaluate the combined impacts of inundation on this military installation in the lower Chesapeake Bay. The naval base topography and nearshore water body of Hampton Roads were included in the coastal modeling system (CMS), a suite of surge, circulation, wave, sediment transport, and morphology evolution models. The modeling domain was a rectangular area covering the entire Naval Station Norfolk in the Hampton Roads and the mouths of the James and Elizabeth rivers. A variable-resolution grid system was created with a finer resolution of 10 m in the naval base and a coarser resolution of 300 m in the regions away from the base. The boundary-forcing conditions to the CMS were regional storm surge produced by the ADvanced CIRCulation (ADCIRC),and wave conditions by the Simulating WAve Nearshore (SWAN) model. The CMS calculated the local water-surface elevation and storm-surge inundation for combined RSLR, surge, waves, and wind. Results indicate that synthetic storms would cause extensive inundation of coastal land around the naval base. Approximately 60% of the land would be under water with the 100-year storm for the present sea level, and 80% for estimated RSLR of 2 m.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**13**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

transport, and morphology change in coastal and inlet applications. It consists of a hydrodynamic and sediment transport model, CMS-Flow, and a spectral wave model, CMS-Wave, and can be coupled with a particle-tracking model. The coupled modeling system calculates time-dependent water elevation, current speed and direction, sediment transport flux, and bottom and land surface erosion and accretion.

CMS-Flow is a two-dimensional (2-D) finite-volume model that solves the mass conservation and shallow-water momentum equations of water motion on a nonuniform Cartesian grid (Buttolph *et al*., 2006; Sanchez *et al*., 2011a,b). Wave radiation stresses and wave parameters are calculated by CMS-Wave and supplied to CMS-Flow for the flow and sediment transport calculations. Water-level, current, and morphology changes are provided to CMS-Wave at user-specified intervals, which is 3 hours in this application.

CMS-Wave is a 2-D spectral wave transformation model that solves the steady-state wave-action balance equation on a nonuniform Cartesian grid (Lin *et al*., 2008, 2011). The model is designed to simulate wave processes that are significant in coastal inlets, in the nearshore zone, in the vicinity of jetties and breakwaters, and in ports and harbors. These processes include wave shoaling, refraction, diffraction, reflection, wave breaking and dissipation, wave-structure and wave-current interactions, and wave generation and growth mechanisms. The model may be used in half-plane or full-plane mode, with waves propagating primarily from open boundaries into the modeling domain. With the reflection option employed, CMS-Wave performs a backward-marching scheme to represent boundary reflection after the forward-marching calculation is completed. The implementation of wave diffraction in the wave-action balance equation is described by Mase (2001). Additional model features include the grid nesting capability, variable rectangle cells, wave transmission, wave overtopping structures, and wave setup/setdown on a beach slope. The wave setup/setdown is computed on the basis of the horizontal momentum equations, neglecting current, surface wind drag, and bottom stresses. For this calculation, change in the mean water level is related to the transfer of wave momentum to the water column due to wave breaking (Dean and Walton, 2009).

CMS-Flow and CMS-Wave can be coupled and operated through a steering module available in the surface-water modeling system (SMS). The framework of CMS is shown in Figure 1. Zundel (2006) provides details about the SMS.

The CMS has been widely applied to open coasts, coastal inlets, bays, estuaries, Great Lakes, and Pacific Islands (Demirbilek *et al*., 2010; Demirbilek and Rosati, 2011; Li *et al*., 2009). Some recent applications include Grays Harbor, Washington; San Francisco Bay and Bight, California; Noyo Bay, California; Galveston Bay, Texas; Matagorda Bay, Texas; Chesapeake Bay; Shark River Inlet, New Jersey; the Big Island of Hawaii, Hawaii; Cleveland Harbor in Lake Erie; and Rhode Island coast and lagoons (CIRP, 2012).

Coupling the flow and wave models and including calculations of sediment transport and morphology change, the present study investigated five RSLR scenarios of 0 (existing condition), 0.5, 1, 1.5, and 2 m that may occur in the next century. From 1927 to 2006, the RSLR at Sewells Point, Virginia (National Oceanic and Atmospheric Administration

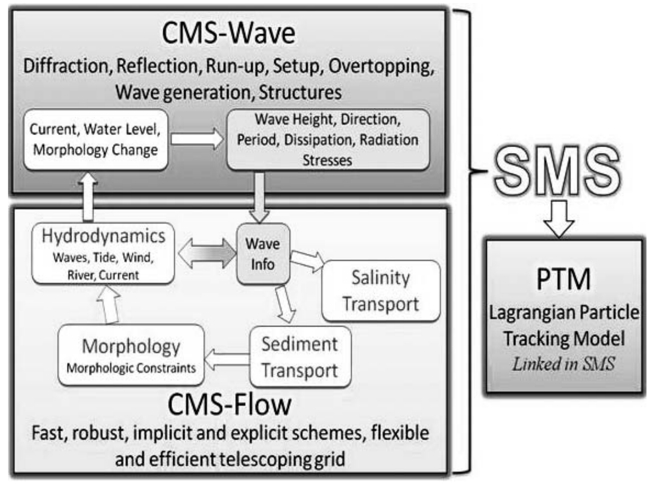

Figure 1. The CMS operational flow chart.

[NOAA] gauge 8638610) was 4.4 mm/y, which is far greater than the global trend of 2.4 mm/y (Jevrejeva *et al*., 2006; NOAA, 2012). Thus, if there is no acceleration in the global trend, RSLR at Sewells Point would be 0.44 m in 100 years. The RSLR scenarios applied in this study were intended to bracket the likely range of future global sea levels, considering the possibility of acceleration in the global trend.

Two synthetic hurricanes (tropical storms) corresponding to 50-year and 100-year return periods and a most probable winter storm (extratropical) that occurred in October 1982 (Burks-Copes and Russo, 2011) were simulated. The selection of the hurricanes was based on 460 synthetic hurricanes designed in a Federal Emergency Management Agency study for the Virginia coast (Blanton *et al*. 2011; Forte *et al*. 2011). The joint probability method with optimal sampling was used to develop the 460 model hurricanes (Vickery *et al*. 2010). The storm parameters include central atmospheric pressure, radius of maximum wind, translation speed, heading, and the Holland B parameter (Holland 1980). The storm return periods were determined primarily by examining water-surface elevations measured at local tidal gauges and storm surges generated by the synthetic hurricanes.

The extratropical storm was selected from 30 historical storms (northeasters) that affected the Norfolk area between 1975 and 2008. The October 1982 storm is one of the most severe storms that affected the region, the selection of which is based on the maximum water-surface elevations measured at the NOAA tide gauges at Sewells Point and Chesapeake Bay Bridge Tunnel in lower Chesapeake Bay. Generally, the peak surge levels produced by extratropical storms are lower, but the surge durations are longer compared with those by hurricanes (days *vs*. hours) (Burks-Copes and Russo, 2011).

On the basis of the five RSLR scenarios and the three selected storms, 15 simulations were conducted (Table 1), each for a 4-day duration including a 12-hour ramping time.

Table 1. *Simulations performed. x' represents a 4-day simulation for the corresponding scenario.*

RSLR (m)	Tropical (50-Year Return) Storm	Tropical (100-Year Return) Storm	Extratropical (Winter) Storm
0.0	x	x	x
0.5	x	x	x
1.0	x	x	x
1.5	x	x	x
2.0	x	x	x

DATA

A collection of coastline information, topographic and bathymetric data, and land surface features in the Hampton Roads area was acquired to develop grids for the CMS simulations. The coastline information in the lower Chesapeake Bay was available from the shoreline database of the National Geophysical Data Center (2011). The aerial photographs were obtained from Google Earth Pro 5.1 (2011). The light detection and ranging (LIDAR) Network (USACE Army Geospatial Center, 2012) provided the land detail topography for Naval Station Norfolk at 1-m resolution and was included in the CMS to describe local land features, such as buildings, roads, airport, and other major infrastructure. Topographic and bathymetric information in other land and water areas was provided with 10-m resolution from the coastal digital elevation model of Virginia Beach (Taylor *et al*., 2008).

Figure 2 shows water depth and land surface elevations relative to mean sea level (MSL), from the two data sets. The figure displays the deep-draft Hampton Roads navigation channel running across the northern portion of the domain, the Norfolk Harbor entrance channel that runs north to south located just west of the Naval Station, and a few small channels to the military piers on the Naval Station waterfront. The data range from the highest elevation of more than 30 m above MSL, including building heights (negative values), to more than 30 m below MSL in the navigation channel (positive values). The red color in the lower left corner indicates the Craney Island Dredged Material Management Area. The dikes built surrounding the area have a height of about 12 m above MSL. Figure 3 shows the areal variations and areal percentage proportional to the total area of Naval Station Norfolk (the blue line polygon in Figure 2) as a function of the variations of land elevation. The figure indicates that 80% of the Naval Station has a land elevation of less than 5 m and 70% between 1 and 4 m. The land coverage data reflect detailed land features in the Naval Station Norfolk. Figure 4 shows different colors delineating land coverage relating to grass, forest, concrete (paved roads, parking lots, and buildings), piers, and dirt roads. On the basis of these data, sediment grain size, erodibility characteristics, and bottom friction were specified at each computational cell in the CMS (Table 2). Because the Naval Station Norfolk and its surrounding area are largely covered by concrete surfaces and buildings, a large part of land surface was treated as nonerodible (hard bottom). A median grain size of 0.2–0.5 mm was specified for the erodible land area

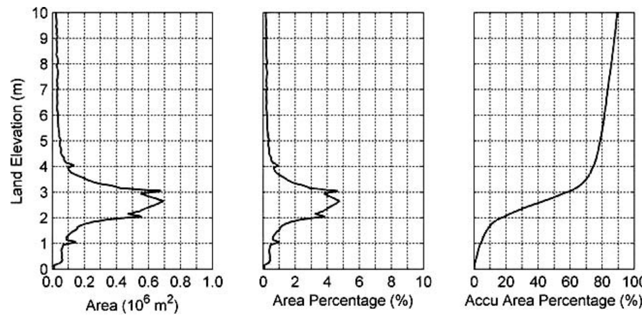

Figure 3. Areal distribution as a function of land-surface elevation (relative to MSL) in Naval Station Norfolk

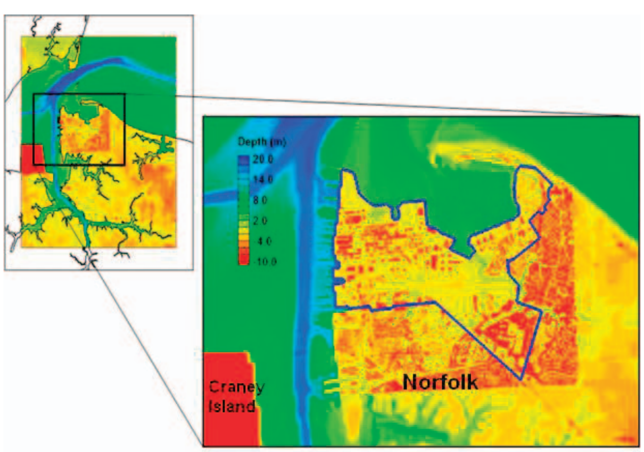

Figure 2. Topographic map of the study area. The blue line outlines Naval Station Norfolk. (Color for this figure is available in the online version of this paper.)

Figure 4. Land coverage (5×5 m) at Naval Station Norfolk. (Color for this figure is available in the online version of this paper.)

Table 2. *Specifications of land erodibility and sediment grain size in the CMS based on land coverage data. N/A = not applicable.*

Land Cover	Erodibility	Grain Size (mm)
Grass	None	N/A
Forest	Limited	0.3
Building	None	N/A
Paved road	None	N/A
Dirt road	Limited	0.5
Parking lot	None	N/A
Pier	N/A	N/A

surrounding Norfolk. As shown in Figure 4, those areas include the dirt road, forest, and grass.

MODEL SETTING

The regional models, ADvanced CIRCulation (ADCIRC; Melby *et al.*, 2005) and Simulating WAve Nearshore (SWAN; http://www.swan.tudelft.nl), provided waves, wind, and surge-level input at the CMS boundary for two synthesized hurricanes with 50-year and 100-year return periods and a winter storm (northeaster). Figure 5 shows the CMS domain with a small portion of the regional grid displayed in the background surrounding the Naval Station Norfolk. The western open boundary of the CMS is located in the mouths of the James and Elizabeth rivers, the northern and eastern open boundary are in Chesapeake Bay, and the southern open boundary mainly crosses the land south of the city of Norfolk. The CMS nonuniform rectangular grid has more than 500,000 grid cells, which permits finer resolution with 10-m spacing in areas of high interest such as Naval Station Norfolk.

Figures 6 and 7 show wind and wave conditions associated with the 100-year return storm, respectively, at a location adjacent to the eastern open boundary. Both the wind and wave

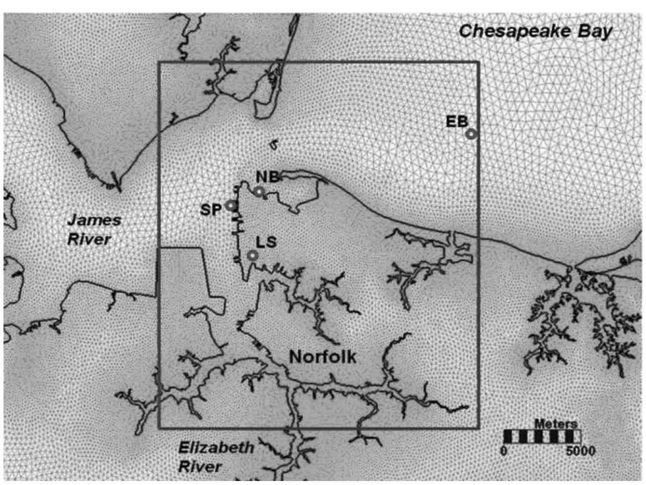

Figure 5. Study area. The rectangle delineates the CMS domain and triangles indicate the regional model mesh. Cycles are time series sites at Sewells Point, west of the naval base (SP), north of the base (NB), the eastern open boundary (EB), and on land (LS).

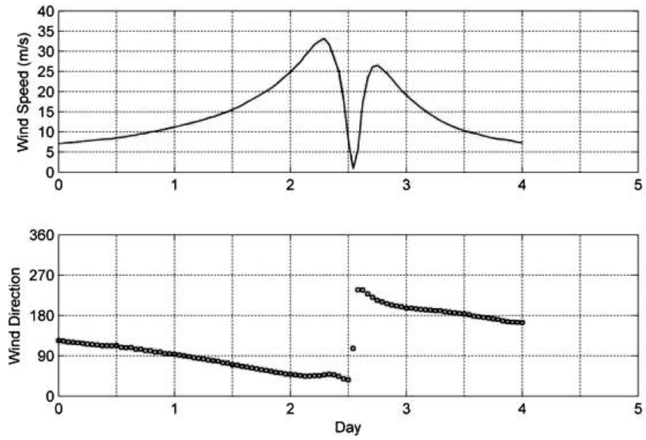

Figure 6. Wind speed and direction of the 100-year return storm.

directions follow meteorological convention where a direction of 0° indicates the wind blowing or wave propagating from the north. Local wind speed and direction were extracted from ADCIRC simulations for the same storms. The wind plots indicate that the tropical storm passing over the study area has a peak wind speed of 33.2 m/s (74.3 mi/h). Incident storm waves provided by SWAN propagate from the Atlantic Ocean with a wave period of 16.7 seconds and a peak wave height of 4.3 m.

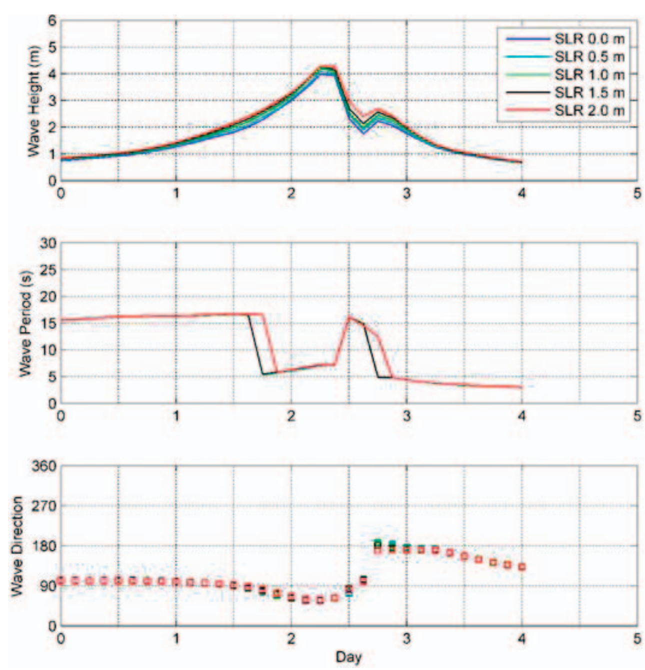

Figure 7. Wave parameters of the 100-year return storm under the existing condition and four sea-level-rise scenarios. (Color for this figure is available in the online version of this paper.)

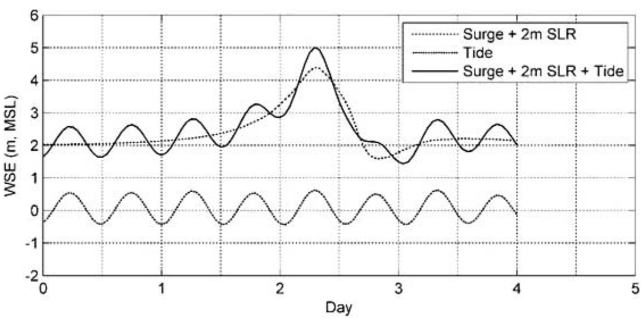

Figure 8. Surge, 2-m sea-level rise, and tide at NOAA gauge 8638610 (Sewells Point, Virginia).

Astronomical tidal data representing 4 days of a spring tide at Sewells Point, Virginia (NOAA, 2011) were incorporated into the storm surge provided by ADCIRC for each of the RSLR conditions in the CMS. The superposition of tide and storm surge provided the water-surface elevation forcing along the CMS open boundary. Figure 8 shows the 2-m RSLR scenario, in which the spring tide increased the maximum water-surface elevation by more than 0.5 m at the forcing boundary.

A long-term increase in RSLR will inundate land and eventually create or destroy wetland areas along coastal regions. To accurately calculate nearshore hydrodynamics, the storm-surge models represent these long-term effects of SLR by a change in vegetation types with corresponding adjustments in bottom frictional roughness (McAlpin, Wamsley, and Cialone, 2011). Consistent with the regional surge and wave models, the CMS used four sets of bottom roughness (Manning's n values) for the four SLR scenarios. For example, for the 2-m RSLR scenario (Figure 9), a small Manning's n of 0.02 was specified for open-water areas and increased to 0.15 for vegetation coverage on land (Chow, 1959).

CMS-Flow and CMS-Wave were dynamically coupled during the simulation at a 3-hour interval. CMS-Flow calculated current, water level, and morphology change and transferred this information to CMS-Wave. CMS-Wave used this information along with incident wave spectra to calculate and transfer wave radiation stresses and wave parameters (height, period, and direction) to CMS-Flow to complete one coupling cycle. This process was repeated for the 4-day duration of each simulated storm.

VALIDATION WITH HURRICANE ISABEL

The CMS capability for nearshore surge calculations was validated with measurements from Hurricane Isabel, a devastating hurricane that affected the Norfolk area in September 2003. Specification of the primary driving forces for Hurricane Isabel is similar to what was described above for the synthesized storms and will not be repeated here. Figure 10 shows the input water-surface elevation and wind data, with the maximum level at 1.9 m above the MSL and maximum wind speed of approximately 29.0 m/s. Figure 11 shows the input wave conditions with a maximum wave height of 3.5 m

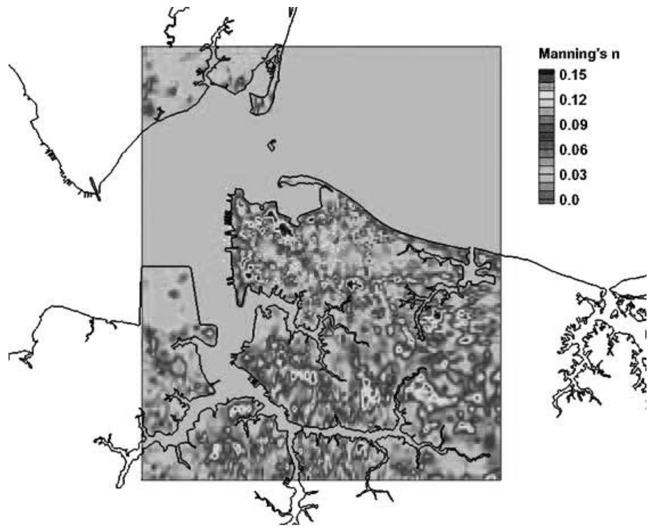

Figure 9. Spatially varying Manning's n under the 2-m sea-level-rise scenario.

with predominant wave direction from the east and perpendicular to the bayside boundary of the CMS domain.

The CMS simulated Hurricane Isabel for the period from September 15 to 19, 2003. The model performance was examined by the comparison of the calculated and measured

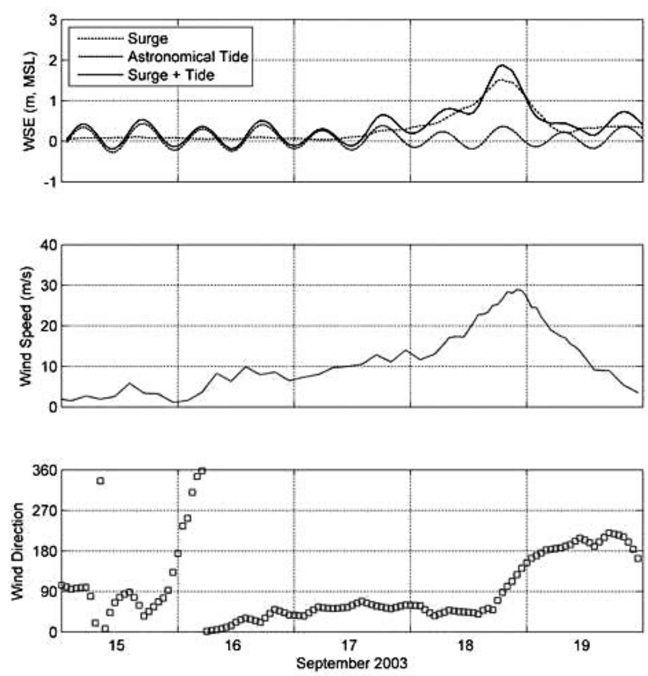

Figure 10. Surge, tide, and wind of Hurricane Isabel at NOAA gauge 8638610 (Sewells Point, Virginia).

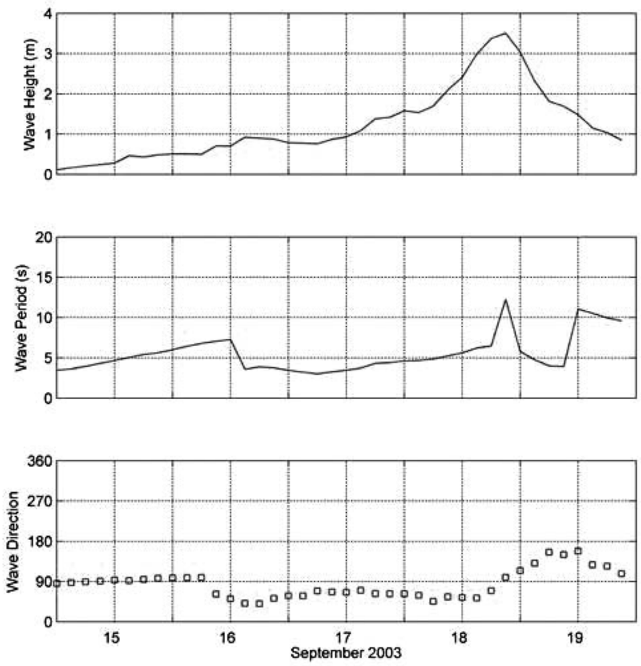

Figure 11. Wave parameters of Hurricane Isabel.

water-surface elevation at Sewells Point, Virginia as shown in Figure 12. The correlation coefficient between the CMS-calculated water levels and the measured data is 0.990. The root mean square error (RMSE) and the relative RMSE (RMSE/data range) are 0.076 m and 3.6%, respectively.

Comparing the synthesized water-surface elevation specified at the CMS open-boundary in Figure 10 with the calculated results in Figure 12, it can be seen that the storm surge propagates from the bayside as indicated by the phase difference between surge levels at the coastal and the boundary locations. As the surge waves approach the nearshore shallow area, the water-surface elevation at Sewells Point has a 0.1-m amplitude increase and a 1-hour phase lag. The validation

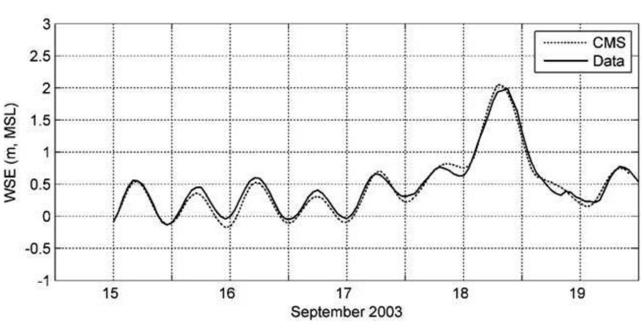

Figure 12. Water-surface elevation comparison between the calculations and measurements of Hurricane Isabel at Sewells Point, Virginia.

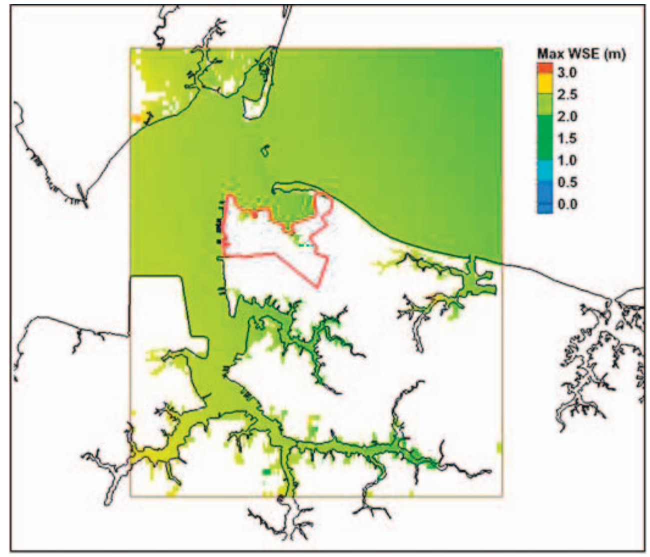

Figure 13. The maximum water-surface elevation due to Hurricane Isabel. (Color for this figure is available in the online version of this paper.)

process shows that the coastal effects on the changes in surge amplitude and phase from deep to shallow waters are well represented in the CMS.

Figure 13 shows the spatial distribution of the maximum water-surface elevations. The simulation results indicate that about 6% of the land area around the military installations was inundated from Hurricane Isabel. The flooded areas are generally flat and have a ground elevation of less than 2 m above MSL. Because waves break in shallow water, the CMS-calculated significant wave heights at the flooded area have a small averaged value of 0.08 m. Additional flooded areas due to wave effects can be estimated by the peak surge level of 2 m and the relationship between the change in land elevation change and flooded area percentage (Figure 3). To investigate this effect, water levels were increased by 0.04 m, half of the averaged significant wave height, which resulted in an increase in the corresponding area changes of 1.0% of the total area. Therefore, a relatively large response to overland inundation should be expected if wave effects are considered besides surge, tide, and wind.

The most severe land inundation in the Hampton Roads area was caused by the rainfall-led flash flooding and river flooding during Hurricane Isabel (http://en.wikipedia.org/wiki). The post-Isabel flooding damage at Naval Station Norfolk was described and three inundated areas by the storm surge were identified by Angela Schedel and Eugene Lambert (*personal communication,* June 5, 2012). As shown in Figure 14, those areas include a parking lot (PKL), the Naval Base Golf Course, and an area adjacent to Mason Creek, all located in the northern side of the base. No flooding map is available for Hurricane Isabel, which presents difficulties for a quantitative comparison between the model results and the survey data. However, the three flooded spots correspond well to the

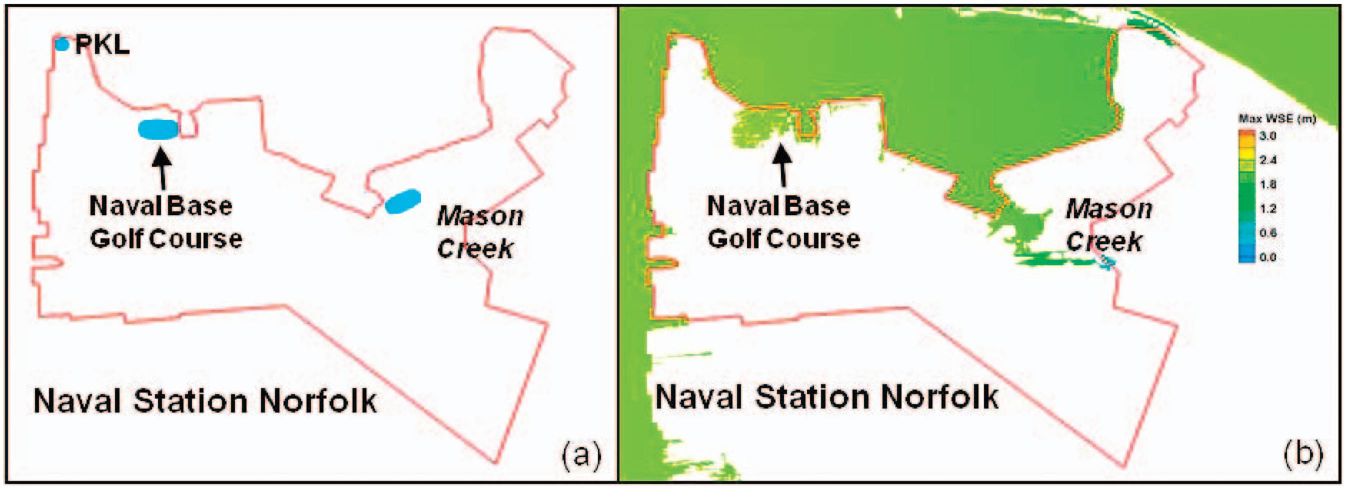

Figure 14. The post-Isabel flooded locations at Naval Station Norfolk. (Color for this figure is available in the online version of this paper.)

calculated flooding coverage based on the maximum surge level (Figure 13).

RESULTS OF SYNTHETIC STORMS

The CMS simulated the existing condition (0 m RSLR) and four other RSLR scenarios (0.5, 1, 1.5, and 2 m) for Naval Station Norfolk with three selected storms, the 50-year and 100-year-return tropical storms and an extratropical storm. The storm-induced inundation was investigated and evaluated by surge, waves, and wind effects.

Storm Surge

Surge level is analyzed as an important indicator of land inundation under the existing condition and four RSLR scenarios for three selected storms. Figures 15 (a) and (b) show the maximum water-surface elevations under the existing condition and the 2-m RSLR scenario for the 100-year return storm, respectively. Because Naval Station Norfolk has land surface elevations generally less than 4 m above MSL, most areas could be under the maximum surge level for the simulated storm. The greater land elevations east of the Naval Station, Craney Island to the west, and some tall buildings stay above the maximum surge level under the 2-m RSLR scenario.

Calculated water-surface elevations were examined at four locations: sites EB, SP, NB, and LS (Figure 5), located at the eastern boundary, Sewells Point, north of the Base, and a land site, respectively. Figure 16 shows the calculated water-surface elevations at the four sites for the existing condition and four SLR scenarios with the 100-year storm. Site LS is located on Naval Station Norfolk and has a land elevation of 2.0 m above the present MSL. Therefore regular tidal conditions cannot flood the site under the 0.0, 0.5, and 1.0 m SLR scenarios. The wetting and drying process at the location is displayed by the discontinuity of the water-surface elevations in Figure 16.

Tidal and surge signals at sites SP and NB coincide with tidal forcing implemented at the model open boundaries, but the surge levels are generally higher. The difference in surge between sites SP, NB, and EB can be as large as 0.4 m, which clearly displays the nearshore water pileup as tidal waves propagate from open water to the harbor area. A different inundation picture is shown at site LS. Normal tidal conditions would not flood the installation area adjacent to this location for the existing condition, the 0.5-m, and 1-m SLR cases, but would for the 1.5-m and the 2-m SLR cases. The storm surge would raise the peak water level to 3.643 m under the existing condition and to 5.430 m under the 2.0-m SLR scenario.

Table 3 presents a list of areas inundated because of the 50-year and 100-year tropical storms and the extratropical storm, with different SLR scenarios for Naval Station Norfolk. The results show that the flooded area expands as the RSLR increases from 0 to 2.0 m. Among the three simulated storms, the 100-year storm inundates more than 60% of the area for different RSLR scenarios. All three storms cause inundation of approximately 60–80% of Naval Station Norfolk under the 2-m RSLR scenario.

The CMS results showed that Hurricane Isabel did not cause severe flood damage in Naval Station Norfolk. In comparison, the peak surge level of the 100-year storm is nearly twice that of Hurricane Isabel under the present MSL (2.0 m *vs*. 3.6 m). This significantly higher peak water level could result in flooding more than 60% of Naval Station Norfolk. Comparing Hurricane Isabel with the three synthesized storms, the 50-year return storm causes a similar land inundation within the Naval Station.

Waves

Along the CMS grid open boundaries, large significant wave heights propagate into the model domain, decrease, and break as waves approach nearshore toward the harbor and overtop the low land area. Figures 17 (a) and (b) show the maximum significant wave heights under the existing condition and the 2-m RSLR scenario at the peak of the 100-year return storm,

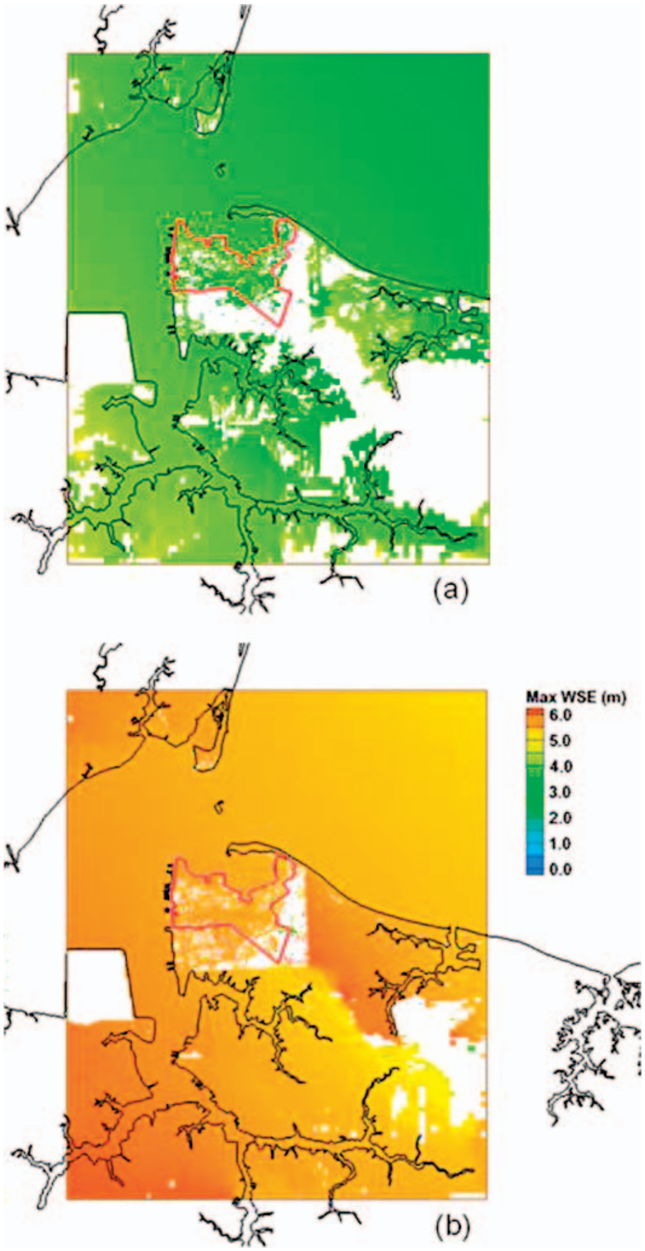

Figure 15. The maximum water-surface elevation due to 100-year return tropical storm under (a) the existing condition and (b) the 2-m RSLR scenario. (Color for this figure is available in the online version of this paper.)

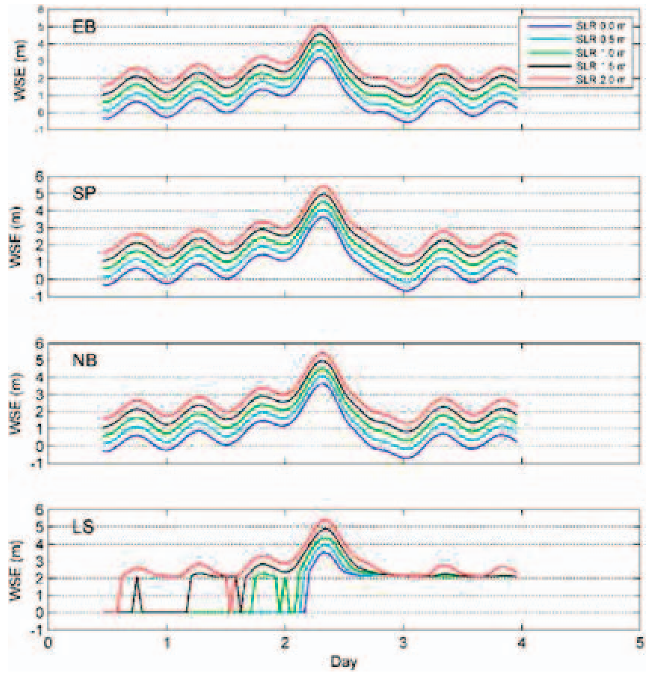

Figure 16. Water-surface elevation of the 100-year return tropical storm under the existing condition (0 m) and the four sea-level-rise scenarios at sites EB, SP, NB, and LS. (Color for this figure is available in the online version of this paper.)

respectively. Wave heights over the flooded area at Naval Station Norfolk are consistent during the maximum surge and generally have amplitude of a few centimeters. Relatively large wave heights (greater than 1.0 m) can be identified in the figure, as seen close to the bayside front of the Naval Base for different SLR scenarios. North of the CMS domain the wave height can reach 6.0 m under the 2-m SLR scenario. The time series of forcing conditions and model output reveal that waves propagating from the Chesapeake Bay side encounter strong opposite wind- and tide-induced currents along the navigation channels during the storm passage, and the strong wave-current interaction seems to induce the large waves at this location.

Figure 18 shows the time series of significant wave height, wave period, and wave direction at sites SP and NB. The calculated wave parameters displayed at EB are similar to the waves specified at the open boundary (Figure 6). Waves have dissipated and diffracted as they approach Hampton Roads along the coast. The coastal effects on wave propagation are evident from calculated wave results at site SP. Dominant wave directions are from the west under the existing condition, 0.5-m, and 1.0-m RSLR scenarios or from the north under the 1.5-m and 2-m RSLR scenarios at site SP. Small short-period wind waves are mostly propagating from the west and long-period swells reach the site from the north. Figure 18 also shows that waves from the northeast have a direct impact on site NB. The wave heights at the two sites indicate that the flooded land areas related to wave activities could be small and negligible.

Estimates of the inundated areas in Table 3 are based on surge- and tide-induced water level. To account for wave effects in the calculations, one-half of the significant wave heights are added to obtain the maximum water mark associated with storms. The wave-modified water level will result in changes in flooded areas at Naval Station Norfolk. The maximum significant wave heights within Naval Station Norfolk (Figure 2) were averaged and the results are shown in Table 4 for three

Table 3. *Area and area percentage flooded in Naval Station Norfolk (10^6 m^2) for three storms under the existing condition (0 m) and four different relative sea-level-rise scenarios.*

	50-Year Return Storm		100-Year Return Storm		Northeaster	
RSLR (m)	Area	%	Area	%	Area	%
0.0	1.176	8.11	9.076	62.57	1.662	11.46
0.5	2.720	18.75	10.219	70.45	3.839	26.47
1.0	4.948	34.11	10.762	74.20	7.326	50.51
1.5	8.198	56.52	11.078	76.37	9.811	67.64
2.0	10.014	69.04	11.317	78.02	10.626	73.26

storms under the existing condition (0 m) and four other RSLR scenarios. The averaged wave height ranges for the 50-year, 100-year, and the northeaster storms are 0.01–0.08 m, 0.12–0.15 m, and 0.14–0.20 m, respectively. Because of different storm characteristics, the northeaster generated the largest wave height within Naval Station Norfolk.

Possible area changes due to the wave-induced water-level changes are demonstrated by the 100-year storm. Figure 15 shows that the peak water level (surge and tide) reaches to 3.643, 4.081, 4.511, 4.975, and 5.430 m under the existing condition (0 m) and four other RSLR scenarios (0.5 m, 1 m, 1.5 m, 2 m) at site SP, respectively. Considering water-level changes of 0.07, 0.06, 0.07, 0.07, and 0.08 m (half of significant water heights), the corresponding area changes are 0.75, 0.56, 0.28, 0.23, and 0.23% of the total area on the basis of the relationship between land area and land elevation (Figure 3). The flooded area changes due to the wave effects are listed in Table 4 for all three storms. Compared with Hurricane Isabel, the area changes due to waves are relatively small as a ratio to the total land inundation for the 50-year and 100-year storm and the northeaster. But the absolute flooded area changes, 2.6 to 4.0% of the entire Naval Station, are more significant for the northeaster under the existing condition, 0.5-m, and 1-m RSLR scenarios.

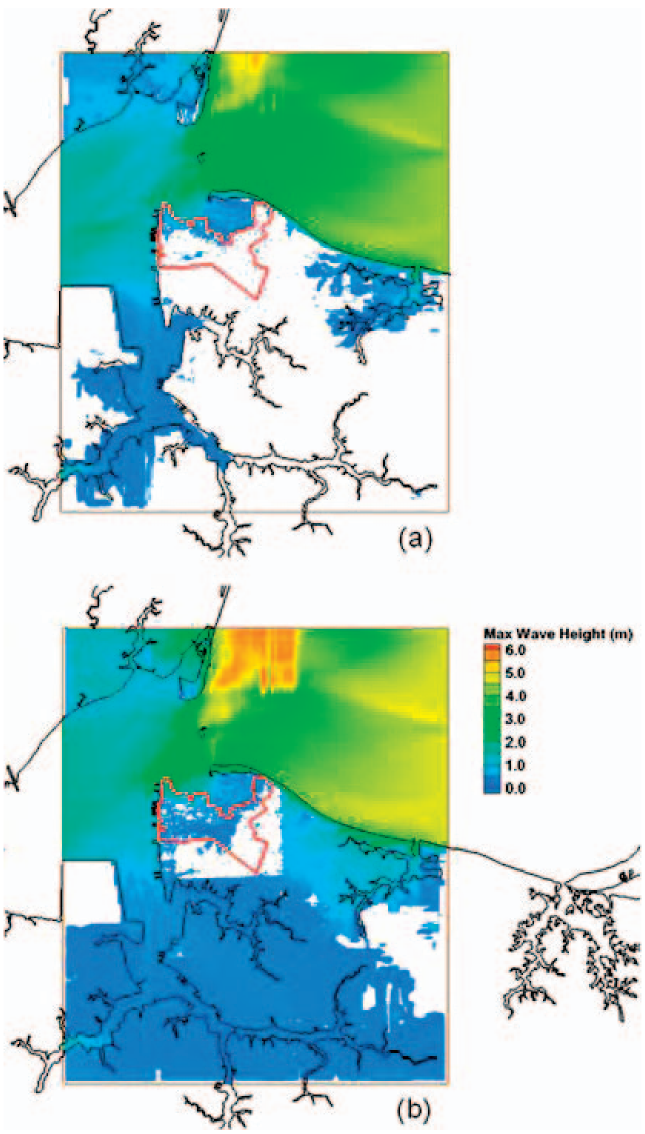

Figure 17. The maximum wave height due to 100-year return tropical storm under (a) the existing condition and (b) the 2-m RSLR scenario. (Color for this figure is available in the online version of this paper.)

Inundation Induced by Wave and Wind Setup/Setdown

Physical processes associated with water-level change and land inundation are wind- and wave-driven setup/setdown, tide elevation, and wave breaking and runup/overtopping in nearshore areas. To understand these processes at Naval Station Norfolk, the primary forcing terms, wind, tide, and waves were examined for the 100-year return storm under the existing condition (0 m) and the 2-m SLR scenario. The model results were compared for each simulation with full hydrodynamics and wave forcing, without wave forcing, and without wind forcing.

Table 5 displays the maximum water-surface elevations at the two coastal sites (NB and SP), and the one offshore site (EB). Because the northern coastal site is open to the Chesapeake Bay and the western site is sheltered by the coastline from the bayside (Figure 9), the peak surge level responds to waves and wind differently as the 100-year storm waves approach from the bayside. Table 5 also indicates that shoreward-directed surge could cause about 0.4–0.5 m of water buildup against the coast. Waves do not result in noticeable setup/setdown at sites SP and NB. Wind is more effective at changing water level. As shown in Table 5, wind setup and setdown can cause about 0.1 m of

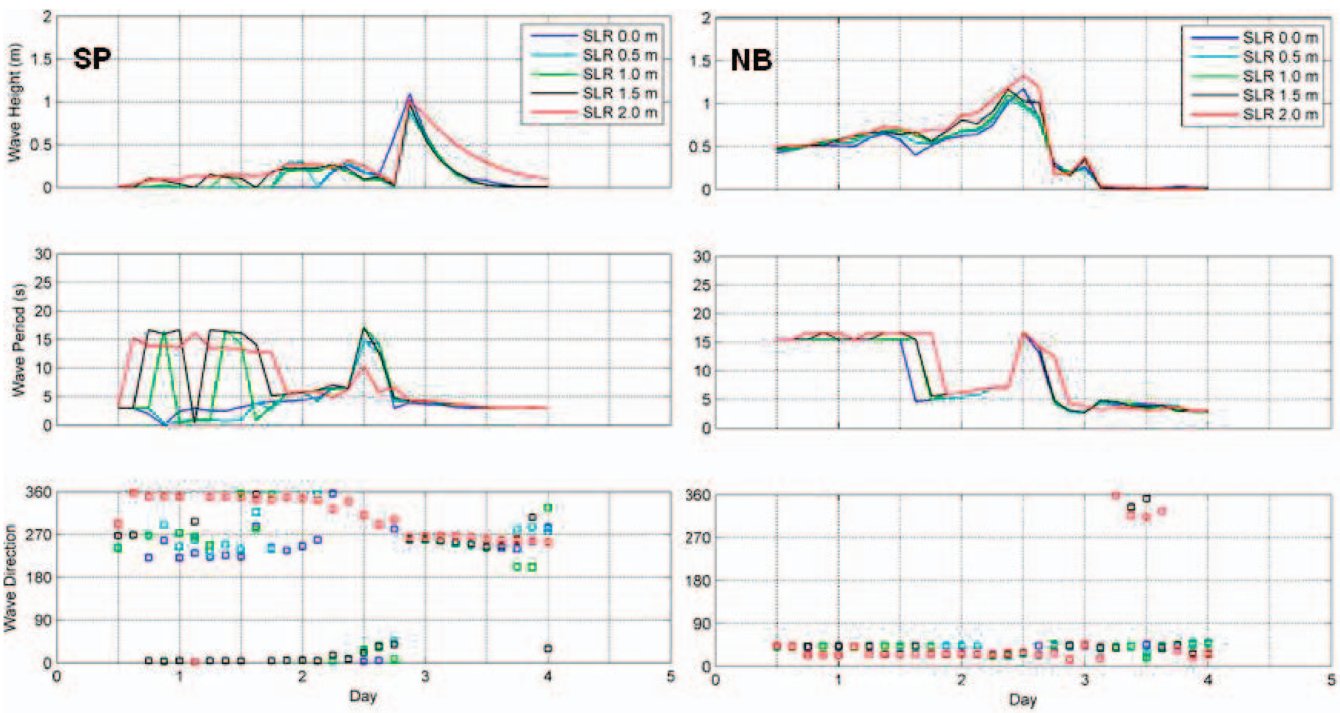

Figure 18. Wave parameters of the 100-year return tropical storm under the existing condition (0 m) and the four sea-level-rise scenarios at sites SP and NB. (Color for this figure is available in the online version of this paper.)

water-level increase and decrease at the northern coastal site and Sewells Point, respectively.

Table 6 presents the land inundation corresponding to wave- and wind-induced water-surface elevation changes. The 0.01–0.02-m wave setup has a minor impact on the amount (less than 0.5%) of flooded area of Naval Station Norfolk. Wind-induced water-level changes are much larger and result in an increase of inundated area of 6% under the existing condition, but the area increase due to wind is trivial under the 2-m RSLR scenario. The different area change is determined by peak surge-level values, which are 3.643 and 5.430 m for the existing condition and 2-m RSLR scenario, respectively. As shown in Figure 3, a 0.01-m change in water level around the 3.6-m land elevation corresponds to greater than 1% of the total flooded area, whereas around the 5.4-m elevation, the same water-level change only corresponds to an increase of less than 0.3% of the total flooded area.

A similar pattern of wave- and wind-induced setup/setdown is seen for Hurricane Isabel at the coastal and boundary sites, although Hurricane Isabel generated a much smaller peak surge of about 2 m (Table 5). Figure 3 indicates that the flooded area can fluctuate by 3–4% of the total area in the naval base if water-surface elevation varies within 0.01 m around the 2-m surge level. This result is different for the 100-year storm case in which the land inundation increases because of wind. Table 6 indicates that the wind effect of Hurricane Isabel corresponds to a smaller inundated area. The flooded area reduction at this surge level seems more sensitive to and more closely related to wind setdown at Sewells Point.

The calculations of water-surface elevation and coastal inundation were performed by the coupled modeling system with the different SLR scenarios. The results demonstrate that the interactions between currents and waves, atmospheric forcing, bathymetric and coastline effects, and topographic

Table 4. *Area-averaged maximum significant wave heights (m) and corresponding area change as a ratio to the total area (%) for three storms under the existing condition (0 m) and four different sea-level-rise scenarios in Naval Station Norfolk.*

	50-Year Return Storm		100-Year Return Storm		Northeaster	
RSLR (m)	Wave Height (m)	Area Change (%)	Wave Height (m)	Area Change (%)	Wave Height (m)	Area Change (%)
0.0	0.01	0.22	0.13	0.75	0.20	3.96
0.5	0.01	0.27	0.12	0.56	0.18	3.67
1.0	0.03	0.59	0.13	0.28	0.19	2.57
1.5	0.08	0.43	0.14	0.23	0.14	0.58
2.0	0.08	0.37	0.15	0.23	0.14	0.35

Table 5. *Maximum water-surface elevations (m) at the coastal locations north and west of Naval Station Norfolk and the eastern open boundary for the 100-year return storm under the existing condition (0 m) and the 2-m sea-level-rise scenario and Hurricane Isabel.*

Scenario	Open Boundary			North of Naval Base			West of Naval Base (Sewells Point)		
	0 m RSLR	2 m RSLR	Isabel	0 m RSLR	2 m RSLR	Isabel	0 m RSLR	2 m RSLR	Isabel
Flow + waves	3.228	5.059	1.872	3.637	5.425	2.058	3.643	5.430	2.055
No waves	3.228	5.058	1.872	3.629	5.413	2.051	3.644	5.428	2.055
No wind	3.232	5.063	1.876	3.518	5.306	2.043	3.740	5.536	2.107

features are all contributing to changes in calculated hydrodynamic variables and inundated areas.

Figure 19 shows sensitivity results of water-surface elevations under the 2-m SLR scenario for the 100-year storm at sites LS, SP, and NB. The comparisons are between the final model setup and the simulations without the wind forcing, with a constant Manning n of 0.05 on land, without the CMS-Wave, and with the half-plane wave model in Figures 19 (a), (b), (c), and (d), respectively. Clearly, the wind setup/setdown causes the greatest departure of water-surface elevation from the mean water level under the storm condition and the switch from the full-plane wave model to the half-plane model produces the least water-level changes. Water-surface elevations show stronger response to the changes in wind and bottom friction at the shallow water site (LS). Because the 100-year storm has a direct impact on the northern side of Naval Station Norfolk (Figures 6 and 7), both wind and waves induce large water-level changes at site NB. Wave-induced water-level changes seem insignificant at the nearshore sites LS and SP due to wave diffraction, dissipation, and breaking.

Associated with the water-level changes due to different physical processes, the area inundation can be greatly affected in the coastal region. Therefore, it is necessary to apply a comprehensive model, such as the CMS, to study storm surge and storm-induced coastal flooding.

CONCLUSIONS

The CMS, a coupled numerical modeling system of waves, circulation, and sediment transport, was applied to simulate nearshore surge and waves, to estimate inundation, and to examine potential effects of SLR triggered by climate change and storm surge surrounding Naval Station Norfolk. The CMS was validated for water elevation for Hurricane Isabel, and calculated water-surface elevations showed good agreement with measurements at Sewells Point, Virginia. Additional model simulations were conducted for two synthesized tropical storms (50-year return and 100-year return), and one extra-tropical storm (northeaster) under the existing condition (the present MSL) and four RSLR scenarios, 0.5, 1, 1.5, and 2 m.

Table 6. *Area flooded (10^6 m^2) for the 100-year storm under the existing condition (0 m) and the 2-m sea-level-rise scenario and for Hurricane Isabel in Naval Station Norfolk.*

Scenario	100-Year (0-m RSLR)	100-Year (2-m RSLR)	Isabel
Flow + waves	9.076	11.317	0.849
No waves	9.029	11.307	0.834
No wind	8.525	11.308	0.903

The model results indicated that Hurricane Isabel produced a maximum surge of 2 m MSL along the coast and inundated 6% of Naval Station Norfolk. The maximum surge level induced by the 100-year storm reached 3.643 m MSL under the existing condition and to 5.430 m MSL under the 2-m RSLR scenario. Extensive inundation occurred for both of these scenarios. For the three simulated storms the surge levels are high enough to inundate approximately 60–80% of Naval Station Norfolk under the 2-m RSLR scenario. However, the high land area east of the Naval Station, the dredge material placement site at Craney Island, and some tall buildings stay above the extreme surge level during the 100-year return-period storm.

Incident waves were provided along the CMS grid open boundaries. For Hurricane Isabel the nearshore significant peak wave height was 3.5 m. For the synthesized storms significant wave heights were dependent on water depth. Both long-period swells and short-period wind waves were calculated within the CMS domain. The 100-year return-period storm had peak wave heights ranging from 2.5 to 3.8 m under the existing condition and four SLR scenarios. Significant wave heights on Naval Station Norfolk had small amplitudes that averaged between 0.01 to 0.2 m; larger waves of greater than 1 m occurred at the seaward limit of the naval base.

Considering surge and tide only, Hurricane Isabel would inundate 6% of the land area in Naval Station Norfolk. Among the synthesized storms, the 50-year return storm generates the lowest surge level and inundates the smallest land area at Naval Station Norfolk under the same RSLR conditions. On the other hand, the 100-year return storm with the highest surge level inundates the largest land area.

Surge-level changes induced by waves could increase the inundation by 1% of the total area in Naval Base Norfolk for Hurricane Isabel. A minimum inundated area change of 0.22% and a maximum of 3.96% could be related to the waves for the synthesized 50-year storm and the northeaster under the existing condition, respectively. Wave and wind effects on storm surge were examined using Hurricane Isabel and the 100-year storm. Wave setup/setdown is related to 0.01–0.02 m of water-level change, which results in less than 0.5% of changes in flooded area in Naval Station Norfolk. However, wind setup/setdown correspond to 0.01 m of water-level changes and induce greater than 1% and 0.3% of total area changes under the existing condition and the 2-m RSLR scenario, respectively.

The CMS study evaluated coastal inundation caused by storm surge, waves, and wind with global SLR. The model results indicate that Naval Station Norfolk would sustain limited inundation under the existing sea-level condition for storms less than a 50-year return period. Because the

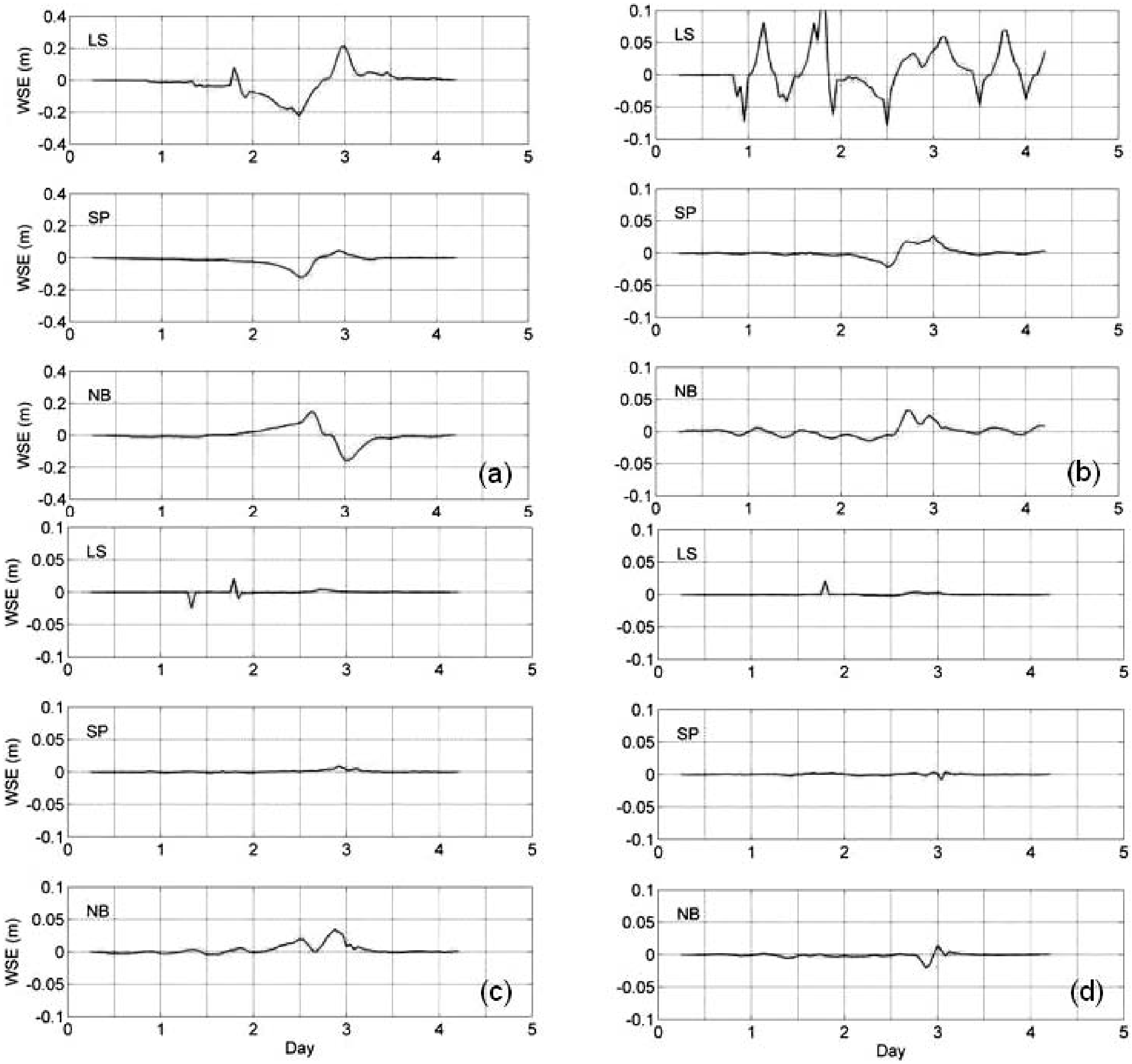

Figure 19. Water-surface elevation differences between the final model simulation and (a) the simulation without the wind forcing, (b) with a constant Manning *n* of 0.05 on land, (c) without the CMS-Wave, and (d) with the half-plane wave model under the 2-m SLR scenario for the 100-year storm at sites LS, SP, and NB.

statistical criteria to define the storms are primarily based on the water-surface elevations, the CMS-calculated inundation does not show linear or nearly linear correspondence with changes in water levels, but rather the combined effects of waves, water level, wind, storm pathway, and storm duration.

The accuracy of the model results is determined by the calculated water-surface elevations and the measurements of land-surface topography. With the high spatial grid resolution and high-quality LIDAR data the CMS presents the inundation results at Naval Station Norfolk and its responses to wave and wind forcing. To improve estimate of water-level change, freshwater inputs (runoffs, precipitation, *etc.*) and 2-D wind and atmospheric pressure fields may be incorporated into future CMS simulations.

ACKNOWLEDGMENTS

We thank the funding support by the Resource Conservation and Climate Change Program Area of the Strategic Environmental Research and Development Program and by the Coastal Inlets Research Program administered at Coastal

and Hydraulics Laboratory under the Navigation Program for Headquarters, U.S. Army Corps of Engineers (USACE). We are grateful for the late Dr. Nicholas C. Kraus for his inspiration and encouragement toward the CMS application to this study. We also thank Dr. Julie D. Rosati, Dr. Zeki Demirbilek, and Ms. Mary A. Cialone of USACE, and two anonymous reviewers for reviewing and providing constructive comments on the manuscript. Permission was granted by the Chief, USACE, to publish this information.

LITERATURE CITED

Blanton, B.; Stillwell, L.; Roberts, H.H.; Atkinson, J.; Zou, S.; Forte, M.; Hanson, J.L., and Luettich, R., 2011. Coastal Storm Surge Analysis: Computational System, Submittal 1.2 to FEMA. *Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-11-1*. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center.

Burks-Copes, K.A. and Russo, E.J., 2011. Risk Quantification for Sustaining Coastal Military Installation Assets and Mission Capabilities. *Interim Technical Report*. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center: Environmental Laboratory.

Buttolph, A.M.; Reed, C.W.; Kraus, N.C.; Ono, N.; Larson, M.; Camenen, B.; Hanson, H.; Wamsley, T., and Zundel, A.K., 2006. Two-Dimensional Depth-Averaged Circulation Model CMS-M2D: Version 3.0, Report 2, Sediment Transport and Morphology Change. *Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-06-7*. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center.

Chow, V.T., 1959. *Open-Channel Hydraulics*. New York: McGraw-Hill Book Co., 680 p.

CIRP (Coastal Inlets Research Program). http://cirp.usace.army.mil (accessed January 3, 2012).

Dean, R.G. and Walton, T.L., 2009. Wave setup. *In:* Kim, Y.C (ed.), *Handbook of Coastal and Ocean Engineering*. Singapore: World Scientific, pp. 1–23.

Demirbilek, Z.; Lin, L.; Smith, J.; Hayter, E.; Smith, E.; Gailani, J.Z.; Norwood, G.J., and Michaelsen, D.R., 2010. *Waves, Hydrodynamics and Sediment Transport Modeling at Grays Harbor, WA.* Coastal and Hydraulics Laboratory ERDC/CHL-TR-10-13. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center.

Demirbilek, Z. and Rosati, J.D., 2011. *Verification and Validation of the Coastal Modeling System*, *Report 1: Summary Report*. Coastal and Hydraulics Laboratory. ERDC/CHL TR-11-10, Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory.

Forte, M.F.; Hanson, J.L.; Stillwell, L.; Blanchard-Montgomery, M.; Blanton, B.; Leuttich, R.; Roberts, H.; Atkinson, J., and Miller, J., 2011. Coastal Storm Surge Analysis System: Digital Elevation Model, Submittal 1.1 to FEMA. *Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-11-1*. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center.

Google Earth Pro 5.1. URL: http://earth.google.com (accessed December 5, 2011).

Hirsch, M.E.; DeGaetano, A.T., and Colucci, S.J., 2001. An east coast winter storm climatology. *Journal of Climate*, 14, 882–899.

Holland, G.J., 1980. An analytic model of the wind and pressure profiles in hurricanes. *Monthly Weather Review*, 108, 1212–1218.

IPCC (Intergovernmental Panel on Climate Change), 2007. *Fourth assessment report*. Available online at: http://www.ipcc.ch/ (accessed July 23, 2012).

Jevrejeva, S.; Grinsted, A.; Moore, J.C., and Holgate, S., 2006. Nonlinear trends and multiyear cycles in sea level records. *Journal of Geophysical Research,* 111, C09012, doi: 10.1029/2005JC003229.

Li, H.; Brown, M.E.; Smith, T.D., and Podoski, J.H., 2009. Evaluation of Proposed Channel on Circulation and Morphology Change at Kawaihae Harbor and Pelekane Bay, Island of Hawaii, HI. *Coastal and Hydraulics Laboratory ERDC/CHL-TR-09-19*. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center.

Lin, L.; Demirbilek, Z.; Mase, H.; Zheng, J., and Yamada, F., 2008. CMS-Wave: A Nearshore Spectral Wave Processes Model for Coastal Inlets and Navigation Projects. *Coastal and Hydraulics Laboratory Technical Report ERDC/CHL TR-08-13*. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Lin, L., Demirbilek, Z., Thomas, R., and Rosati, III, J., 2011. Verification and Validation of the Coastal Modeling System, Report 2: CMS-Wave. *Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-11-10*. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center.

Mase, H., 2001. Multidirectional random wave transformation model based on energy balance equation. *Coastal Engineering Journal*, 43(4), 317–337.

McAlpin, T.; Wamsley, T., and Cialone, M., 2011. *Methodology for Modeling the Effects of Sea Level Rise with the ADCIRC Numerical Model*. ERDC/CHL TN-CHETN-IV-x. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center.

McLean, R.F.; Tsyban, A.; Burkett, A.; Codignotto, J.O.; Forbes, D.L.; Mimura, N.; Beamish, R.J., and Ittekkot, V., 2001. Coastal zones and marine ecosystems. *In:* Mccarthy, J.J.; Canziani, O.F.; Leary, N.A.; Dokken, D.J., and White, K.S. (eds.), *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Cambridge, U.K.: Cambridge University Press, pp. 343–380.

Melby, J.A.; Thompson, E.F.; Cialone, M.A.; Smith, J.M.; Borgman, L.E.; Demirbilek, Z.; Hanson, J.L., and Lin, L., 2005. Life-Cycle Analysis of Mid-Bay and Poplar Island Projects, Chesapeake Bay, Maryland. *Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-05-12*. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center.

National Geophysical Data Center (NGDC). http://www.ngdc.noaa.gov/mgg/shorelines/shorelines (accessed December 5, 2011).

National Oceanic and Atmospheric Administration (NOAA). http://tidesandcurrents.noaa.gov (accessed December 19, 2011).

National Oceanic and Atmospheric Administration (NOAA). http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8638610 (accessed January 9, 2012).

Pfeffer, W.T.; Harper, J.T., and O'Neel, S., 2008. Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science*, 321, 1340–1343.

Sanchez, A.; Wu, W.; Beck, T.M.; Li, H.; Rosati, J.D.; Demirbilek, Z., and Brown, M., 2011a. Verification and Validation of the Coastal Modeling System, Report 4: Sediment Transport and Morphology Change. *Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-11-10*. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center.

Sanchez, A.; Wu, W.; Beck, T.M.; Li, H.; Rosati, J III; Thomas, R.; Rosati, J.D.; Demirbilek, Z.; Brown, M., and Reed, C., 2011b. Verification and Validation of the Coastal Modeling System, Report 3: Hydrodynamics. *Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-11-10*. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center.

Simulating WAves Nearshore (SWAN). http://www.swan.tudelft.nl (accessed December 19, 2011).

Smith, E., 1999. Atlantic and east coast hurricanes 1900–98: a frequency and intensity study for the twenty-first century. *Bulletin of the American Meteorological Society*, 80(12), 2717–2720.

Taylor, L.A.; Eakins, B.W.; Carignan, K.S.; Warnken, R.R.; Sazonova, T.; Schoolcraft, D.C., and Sharman, G.F., 2008. Digital Elevation Model of Virginia Beach, Virginia: Procedures, Data Sources and Analysis. *NOAA Technical Memorandum NESDIS NGDC-7*. Boulder, Colorado: National Geophysical Data Geophysics Division.

USACE (U.S. Army Corps of Engineers) Army Geospatial Center. http://www.agc.army.mil/ (accessed February 29, 2012).

Vickery, P.; Wadhera, D.; Cox, A.; Cardone, V.; Hanson, J., and Blanton, B., 2010. Coastal Storm Surge Analysis System, Storm Forcing, *Intermediate Submission Report 1. 3,* FEMA Region III.

Zundel, A.K., 2006. Surface-water modeling system reference manual—Version 9. 2. Provo, Utah: Brigham Young University Environmental Modeling Research Laboratory.